CHAPTER 8

RF and Acceleration

The RF system for the TeV is somewhat standard compared to the Booster and Main Injector systems but there are a few differences. The beam injected into the Tevatron does not go through transition since it is already above the transition energy. There are no Ferrite bias supplies for the cavities because the frequency change from 150 GeV to 1 TeV is about 1 kHz. Kind of interesting, huh?

Introduction to RF

The Tevatron RF system is comprised of 4 major parts: 1) low level RF signal, 2) high level RF amplification, 3) transmission line, and 4) resonant cavity. Each of these systems will be explained in the following sections.

What is RF? What does RF mean? RF is an abbreviation for radio frequency. Radio frequencies are a form of electromagnetic waves. The frequencies used in the Tevatron RF cavities are specifically in the 53 MHz region. So how does a wave help in the acceleration of a proton, antiproton, or, for that matter, any charged particle? It has to do with the Lorentz force law,

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

where q is the charge of the particle, E is the value of the electric field that the particle is experiencing, v is the velocity of the particle, and B is the magnetic field the particle is going through. For accelerating a particle, we are only concerned with the first part of the equation because the cavities used have no magnetic field when the particle is present.

$$\vec{F} = q\vec{E}$$

The arrows in the equation tell us that the force exerted on a positive charged particle is entirely in the direction of the electric field. So what is the connection between RF and electric field? The answer is

$$E = -\frac{\partial V}{\partial s}$$

where V is the electric potential, also known as voltage, and s is distance through which the voltage changes. For a synchrotron accelerator, like the Tevatron, the distance or displacement is in the longitudinal direction or z direction.

$$E_z = -\frac{\partial V}{\partial z}$$

The pieces are now starting to fall into place. One more piece should complete the picture. In order to create the voltage difference so that the electric field can be formed in the z direction, a gap must be placed within the cavity. The gap needs to have one end at ground potential, 0 volts, and the other end with the applied voltage.

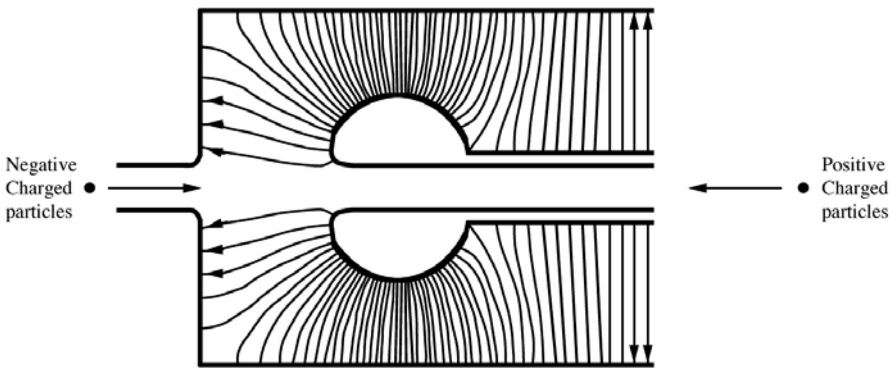


Figure 8.1 This side view of an RF gap shows the electric fields that are formed due to the voltage difference between the cavity shell (0 V) and inner electrode (where the RF voltage is applied).

The picture is now complete. If I take a power supply which applies to the cavity a voltage at a frequency synchronized to the beam then the charged particles will feel a force due to the electric field that is created by the voltage difference across the gap.

Low Level RF

If there is any magic box at Fermilab it is the LLRF VXI system. Booster, Main Injector, and Tevatron use direct digital synthesis (DDS) to create the waveforms output to the RF stations. In the most basic of terms, a DDS system can create any waveform by manipulating a cosine wave. The system carries a ¼ cosine table and can add, subtract, multiply, phase change, etc., that table to create the desired waveform.

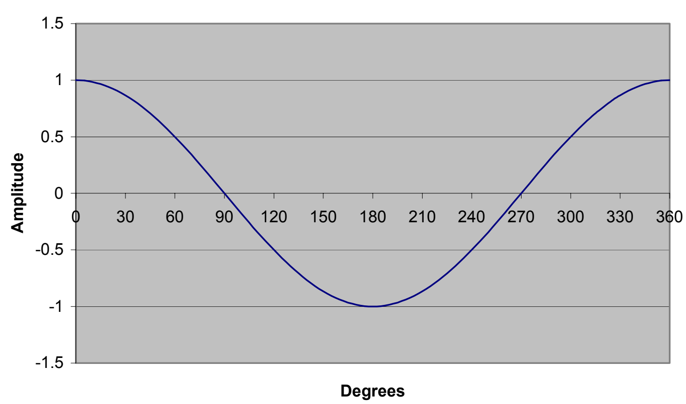


Figure 8.2 The basic DDS system uses 1/4 of a cosine wave to create a desired waveform. A cosine is shown above.

A DDS system can be thought of as a 3 block system. A clock signal and frequency signal, which is represented as a number, are input to a digital accumulator. The waveform map provides the cosine waveform to be manipulated and the output of that is sent to a digital-to-analog converter, which then provides the RF system with the appropriate LLRF signal. The whole system is often called a number controlled oscillator (NCO).

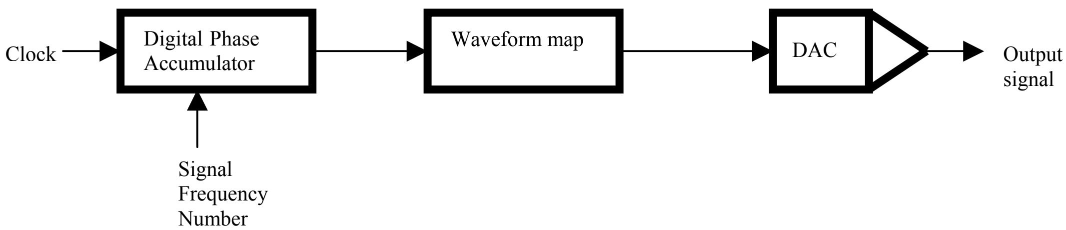


Figure 8.3 DDS system block diagram.

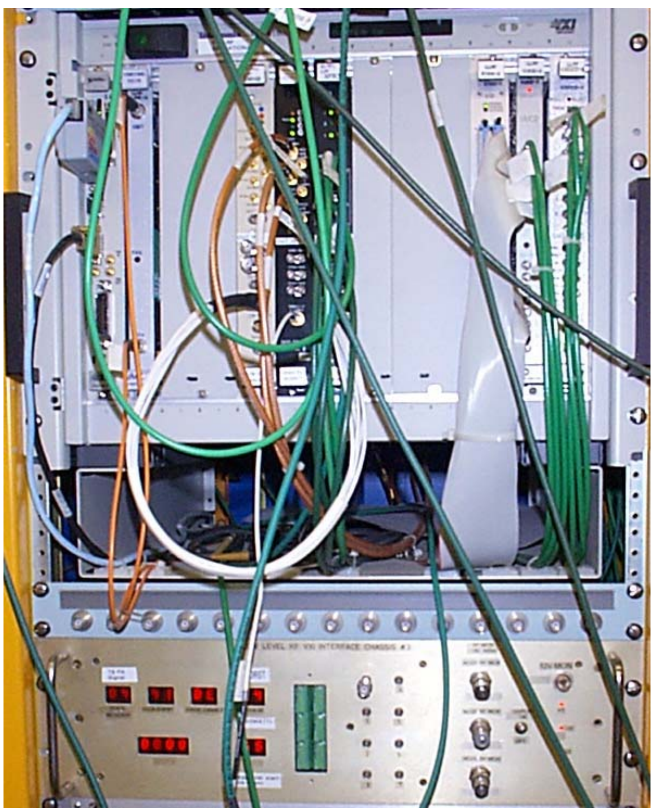


Figure 8.4 The LLRF system housed at MI-60 consists of a VXI system and VXI Interface chassis.

So now that you know the basics of creating a low level signal what does the actual LLRF system look like? The VXI crate that houses the DDS system is located in the control room at MI-60.

The low level system is a combination of software and hardware. An introduction to the basic system diagram was just given but now the intricacies of the software and hardware will now be explained.

The digital signal processor (DSP) and its software create the RF bucket while controlling bucket area, radial beam position, and longitudinal bucket position. This must be done with very little RF phase noise so that the beam is not heated, which could cause beam loss. The software code must perform the frequency and phase calculations and ensure that they are smooth and accurate. The feedforward frequency is calculated from the real time programmed bend bus current, T:MDAT10, which is broadcast at 720 Hz. The frequency calculation is as follows. The frequency of revolution for a particle is

$$f_{rev} = v / 2\pi r$$

where v is the velocity of the particle and r is the radius of the Tevatron, 1 km. The harmonic number of the TeV is h=1113. Multiplying the revolution frequency by the harmonic number gives the frequency of the RF.

$$f_{RF} = hv / 2\pi r$$

If the particle was able to move at the speed of light, of which it cannot because it has a mass, it would take an infinite amount of energy to attain that velocity. The frequency of the particle at this infinite energy is

$$f_{\infty} = \frac{1113c}{2\pi r} = 53{,}105{,}071 Hz$$

where c is the speed of light, 3.0×10^8 m/s. The energy dependence of the RF frequency can be determined by using the relativistic energy

$$E = \gamma E_0 = \frac{E_0}{\sqrt{1 - v^2 / c^2}}$$

where E_o is the rest mass of the particle $m_o c^2$. The above equation can be rearranged to find the velocity

$$v = c\sqrt{1 - \left(\frac{E_0}{E}\right)^2}$$

Since $E \gg E_o$ a Taylor expansion† can be performed on the square root and the first 2 terms used.

$$v = c\left[1 - \frac{1}{2}\left(\frac{E_0}{E}\right)^2\right]$$

Substituting the velocity term into the frequency equation yields

$$f(E) = \frac{hc}{2\pi r} - \frac{hc}{4\pi r}\left(\frac{E_0}{E}\right)^2$$

where the first term is the frequency at infinite energy and the second term is df(E), the change in frequency with respect to energy.

† There are 2 forms used in this document. The form used on this page is $(1 + x)^{½} = 1 + ½ x^2 + \ldots$ The form used on the next page is $(1 + x)^{-½} = 1 - ½ x^2 + \ldots$

$$f(E) = f_\infty - df(E)$$

$$f(E) = f_\infty \left(1 - \frac{1}{2} \left(\frac{E_0}{E} \right)^2 \right)$$

Taking this equation and reapplying a Taylor expansion to it yields an almost final form.

$$f(E) = f_\infty \left(1 + \left(\frac{E_0}{E} \right)^2 \right)^{-\frac{1}{2}}$$

Finally, one more piece of the puzzle is added. The conversion from GeV to amps is 1000 GeV=4440 A, and by knowing this fact the frequency with respect to current can be determined.

$$f(I) = f_\infty \left(1 + \left(\frac{4.44[GeV/A]E_0}{I} \right)^2 \right)^{-\frac{1}{2}}$$

$$f(I) = f_\infty \left(1 + \frac{K}{I^2} \right)^{-\frac{1}{2}}$$

where K is a constant.

$$K = (4.44E_0)^2$$

So now you have it. The software for the LLRF system is written to calculate the appropriate frequency from the programmed ramp current, T:MDAT10 (T:IPROG). The feedforward frequency program resolution is 100 kHz and this gives a precise output to the HLRF system.

The frequency is one calculation a LLRF system DSP needs to perform but usually there is one other calculation that is needed, the synchronous phase ϕ_S. The TeV LLRF system was designed such that it doesn't need to calculate the synchronous phase.

Now, lets discuss the hardware of the LLRF system. Of course, already the DSP has been mentioned but the system contains much more than that. The LLRF system uses the VXI platform so that software and hardware can be incorporated together to generate, with great precision, the required output signals. Other than the VXI, a custom interface chassis is also used to distribute the signals to the RF stations. Both of these components will be discussed below.

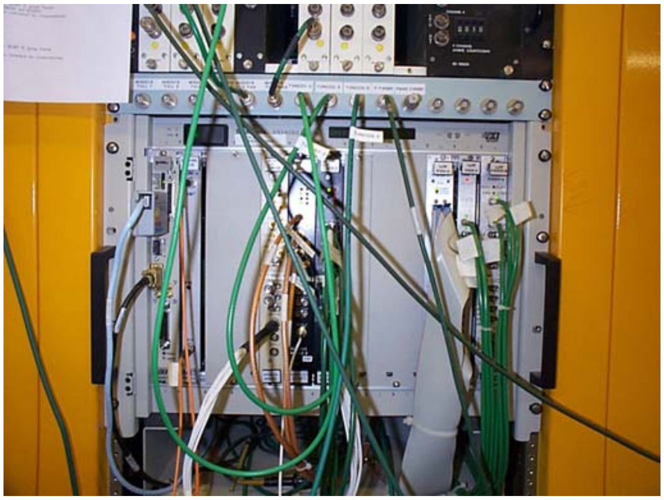


Figure 8.5 The LLRF VXI crate and it associated cards.

The VXI system has 8 cards in the chassis. The card in slot 0 houses the VXI CPU which configures all of the system's devices. An ethernet port on the card provides all of the communication with the ACNET control system. Slot 1 has two fiberoptic connections on the front of the card: transmit and receive. This card is used for reflective memory. All of the LLRF systems are linked by keeping copies of each others code.

An IO100VXI digital I/O module, located in slot 10, generates TTL output signals for the machine states and drives the LED display on the VXI Interface chassis. Slots 11 and 12 house the VME and VXI Universal Clock Decoder modules, which receive and process TCLK, MDAT, and Beam Sync signals. The UCDs sychronize the LLRF system and provide ACNET timing resources for plots.

A 2 channel 200 kHz analog-to-digital converter in Slot 4 converts the beam position and phase detector signals and sends the data to the DDS. The beam transfer information is decoded in the XFR card in slot 6. Beam Sync, MDAT, and Tranfer Sync information is processed and sent to the DDS.

Slot 5 houses the DDS card, where the DSP resides. The output of the DSP (frequency) goes to 3 NCOs, which in turn have their output sent to a phase modulator that amplifies the signal by +17 dBm. The LLRF output signals are carried on 3 gold colored cables. The top cable is for the beam sync system, the middle cable is for the proton RF stations, and the bottom cable is for the pbar RF stations.

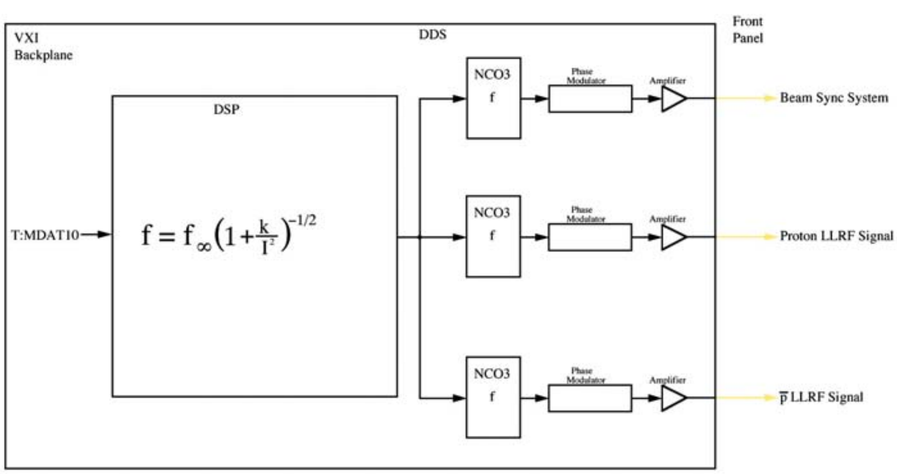


Figure 8.6 DDS board schematic showing the frequency calculation and the output signals.

The above mentioned cables are fed into the back of the VXI Interface chassis, where each signal is sent through a bandpass filter, amplifier, and power splitter. The LLRF signals are then sent to their designated RF station.

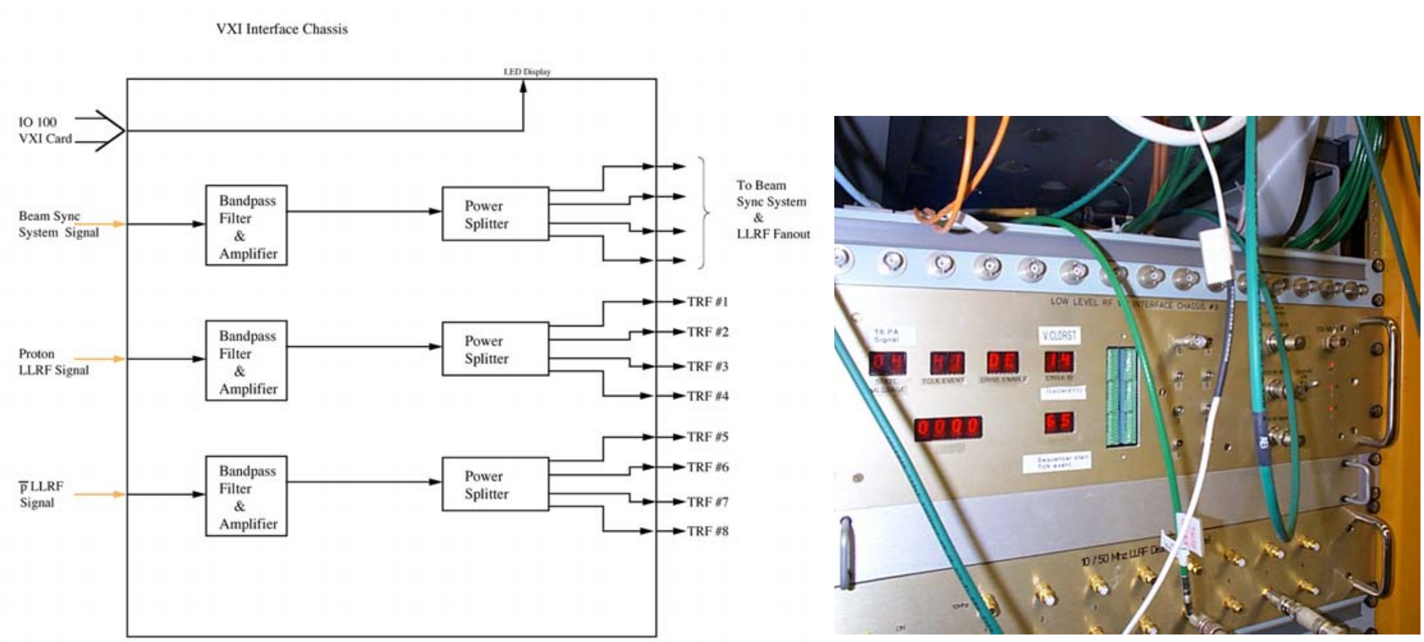


Figure 8.7 VXI interface chassis board schematic and a picture of the chassis at MI-60.

High Level RF

The high level RF is where the amplification of the low level signal takes place. This section of the RF system is very similar to the Booster and Main Injector RF systems except that the Tevatron RF does not employ bias supplies.

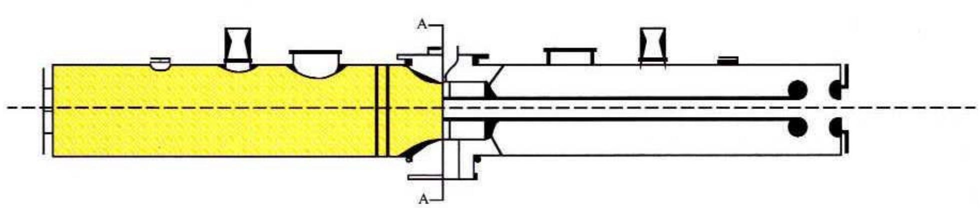
Transmission Line

The transmission line is a means of transporting power from the RF source to the resonant cavity. In essence, it is a distributed capacitor. A coaxial transmission line consists of an inner conductor cylinder and grounded outer cylinder separated by a dielectric medium. In the case for the TeV RF stations the medium is air. An air blower at F0 forces air into the transmission line, which exits through a copper mesh near it’s connection to the RF cavity.

Resonant Cavity

The Tevatron has 8 RF cavities that reside in the F0 straight section. In colliding beams mode they operate as 2 independent groups. Cavities 1, 3, 5, and 7 accelerate antiprotons while 2, 4, 6, and 8 accelerate protons.

Each cavity contains 2 quarter wave resonators with a drift tube separating the 2 acceleration gaps. Refer to the drawing below. The cavity is tuned to operate at 53.104 MHz and a peak voltage of 360 kV (180 per gap). The cavities are kept resonant by a temperature-controlled water system that circulates LCW through the upstream and downstream ends of the drift tube to maintain the 53.104 MHz center frequency.



The high level RF system contains the typical devices used for particle acceleration. An anode power supply provides 35 kV to 8 modulators. The modulators pulse the high voltage to the anode of the PA (power amplifier) through the series tube in the modulator. The anode program, APGS, is input to the grid of the series tube. A 100 W ENI solid state amplifier amplifies the LLRF signal. This signal is sent to the grid of the 14 cascode driver tubes. The cascode drives the cathode of the PA.